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Influence of a built-in potential on electron transport properties of metallic ballistic structures, as evidence of quantum-well effect

G. M. Mikhailov†, I. V. Malikov†, A. V. Chernykh†, E. Olsson‡ and L. Ryen§
† Institute of Microelectronic Technology RAS, 142432 Chernogolovka, Moscow District, Russia
‡ Angstrom Laboratory, Uppsala University, Uppsala, Sweden
§ Chalmers University of Technology, Gothenburg, Sweden

When an electron mean free path becomes comparable to or exceeds the structure dimensions, both inner and outer surface electron scattering begins to determine conducting properties of the multilayered structures. Electron conductivity becomes to be characterised by surface dominated electron transport, and differs essentially from that determined by the bulk structure. Under the conditions, when spatial quantisation of electron momentum due to effect of inner and outer surface potentials comes into the play, the new features are introduced into sliding electron transport of both thin films and nanostructures, composed from the metals. It may lead to the properties, that are unusual for metallic conductors. Here, we present the results of electron transport investigation of Mo-Nb ballistic structures and the effect of interface electron scattering, controlled by built-in potential.

Growth and fabrication. Epitaxial growth of Mo and Nb was performed in super high vacuum chamber by step by step laser ablation of the targets from high purity Nb and Mo onto hearted till 750 °C sapphire ($\bar{1}012$) substrate [1]. At first, the Mo film of 35 nm thick was grown, followed by thin Nb interlayer deposition by single laser pulses target ablation, and, finally, deposition of the second Mo layer of 35 nm thick was performed. The XRD and cross sectional TEM were used for characterization of grown tri-layered films. It is seen from the Fig. 1 that the X-ray peaks (002) and (011) of Mo/Nb/Mo and single-layered Mo film are close each other. Cross-sectional TEM investigations do not reveal

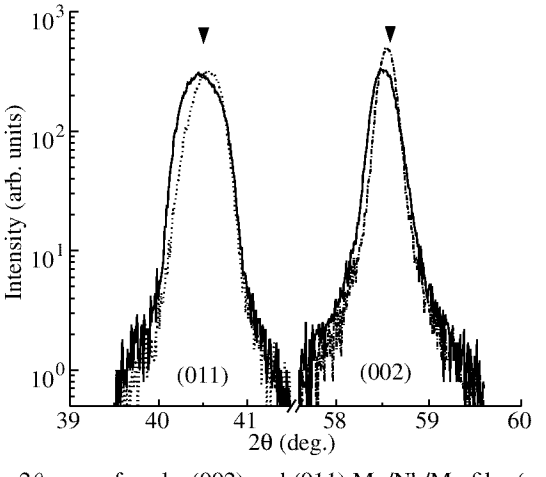

Fig. 1. The XRD $\omega - 2\theta$ scan of peaks (002) and (011) Mo/Nb/Mo film (solid lines), and single layered Mo film (dotted lines). Down triangles show the peak position of the bulk Mo single crystal.

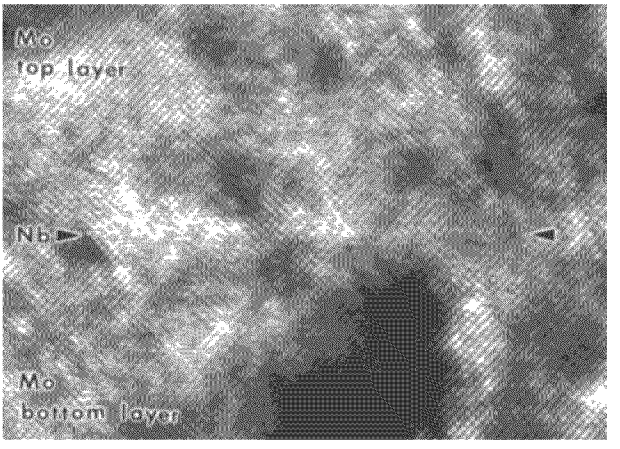

Fig. 2. Cross section of Mo/Nb/Mo film with interlayer Nb thickness in two monolayers. Arrows show Nb minimum of interlayer position. The sample corresponds to the specific resistance oscillation, depicted in Fig. 3 (see text for details).

both distinctive structural defects, associated with thin Nb interlayer, and any difference of the bulk structure between top and bottom Mo layers (Fig. 2). The nanostructures were fabricated down to 200 nm lateral resolution using subtractive electron lithography process, developed earlier [2], additional lithography process was used for Nb leads fabrication.

Electron transport. Specific resistance of tri-layered Mo/Nb/Mo films, determined from lateral electron transport measurements, oscillates upon Nb interlayer thickness with monolayer (0.16 nm) periodicity. It is in effect from room to 9.5 K temperature. The film specific resistance at room temperature differs from that of Mo bulk singlecrystal only in 15%. Min-

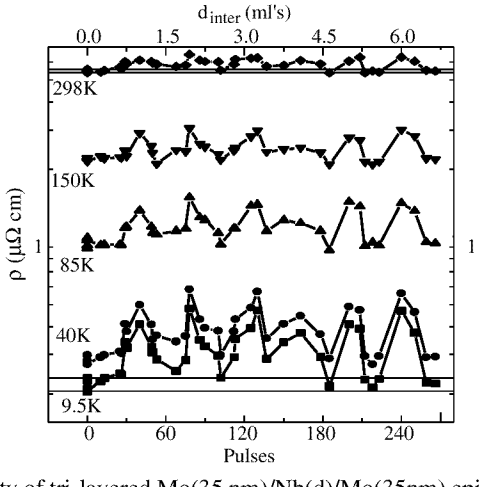

Fig. 3. Specific resistivity of tri-layered Mo(35 nm)/Nb(d)/Mo(35nm) epitaxial films as a function of interlayer Nb thickness (top axis) at the temperatures 298, 150, 85, 40 and 9.5 K. The Nb layer thickness depends on the number of laser pulses during Nb layer growth (bottom axis). Vertical lines are specific resistivity of single layer Mo(001) film of 70 nm thick, defined from controlled experiments.

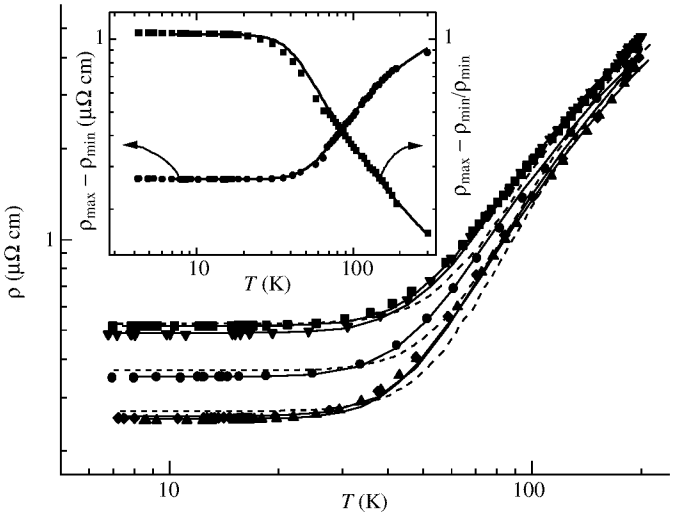

Fig. 4. Temperature dependence of specific resistance in maximum, minimum and in intermediate position of oscillation. (See text for details.)

imum of specific resistivity of tri-layered films corresponds to the Nb thickness with the "half" of each next grown Nb monolayer. It is equal to the specific resistance of single-layered Mo films of 70 nm thick, while for "complete" Nb monolayer growth (maximum) it corresponds to that of Mo single-layered film of 35 nm thick.

Such type behavior is also found in temperature dependence of tri-layered film specific resistance. The amplitude of an oscillation does not exceed more than 15% of specific resistance at 298 K and comes to 100% as the temperature decreases to 9.5 K. Its absolute values are shown in the inserting to the Fig. 4 together with its relative values.

The specific resistance of tri-layered Mo(35 nm)/Nb/Mo(35 nm) films in minimum (diamonds) goes together with that (down triangles) of single-layered Mo film of 70 nm thick and in maximum (squares) with that (up-triangles) of 35 thick. The intermediate values between maximum and minimum (circles) of oscillation are also shown. We used formulae of [3] to fit experimental data, using temperature dependence for bulk mean free path of the film as for bulk Mo single crystal [4] and taking into account both surface scattering and transverse momentum quantisation of sliding electrons [2]. Fitting curves are shown in Fig. 4 and in its inserting as the solid lines. The fitting parameters describe increasing of specific resistivity in each oscillation as an effect of the interface (interlayer) scattering, which we attribute to the built-in potential. Quantum corrections are not small. For comparison we also applied well known effective mean free path model (dashed lines) to fit experimental data. However, it was in lower fitting accuracy. All of these results, together with that of structural characterization (Figs. 1–2) of the films, unambiguously prove that the built-in potential, formed by Nb interlayer, affects on the sliding electron transparency (reflection) through the Nb interlayer, spatial quantisation of transverse electron momentum is important too.

As it will be seen below, the effect of built-in potential is also significant for electron transport through the contact between the strips of nanometer scale. Figure 5 presents the volt-current (V–I) characteristics of the cross type nanostructure composed of epitaxial Mo and disordered Nb strips. The unusual for metals diode effect, appearing as an asymmetric V–I curve, was found. It depends on the temperature and mean free path (m.f.p.) of

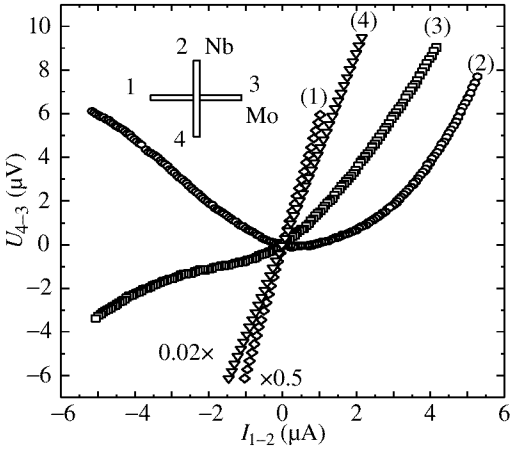

Fig. 5. Bending volt-current characteristic for asymmetric Mo (001)-Nb cross nanostructure with the 400 nm lead width, measured above superconducting transition. Diamonds (1)-Mo strip with effective residual m.f.p. $L_{\text{eff}} \sim 550$ nm at $T = 298$ K, Circles (2)—Mo with $L_{\text{eff}} \sim 550$ nm at $T = 9.5$ K, Squares (3)—Mo with $L_{\text{eff}} \sim 170$ nm at $T = 9.5$ K, Up triangles (4)—Mo with $L_{\text{eff}} \sim 60$ nm at $T = 9.5$ K.

electrons in the epitaxial Mo strip.

We consider the diode effect to be due to the dependence of an electron transparency through the contact area, controlled by built-in contact potential between Mo and Nb strips, both on the direction and the magnitude of the current, passing through the contact area.

New types of metallic low-dimensional structures fabricated on the basis of high-quality epitaxial refractory-metal films possess new properties that are unusual for metallic conductors. It can be attributed to the realisation of the ballistic limit in electron transport leading to sliding electrons come into play and a spatial quantisation of an electron momentum is important. Under this condition, the scattering of conducting electrons is controlled also by the properties of the built-in potential. It gives rise to new phenomena in electron transport of metallic conductors associated with this mechanism.

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